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A heuristic algorithm for U.S. naval mission resource allocation

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MONTEREY, CALIFORNIA

THESIS

A HEURISTIC ALGORITHM FOR U.S. NAVAL MISSION RESOURCE ALLOCATION

by

Derek T. Dwyer

September 2008

Thesis Advisor: Javier Salmeron
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A HEURISTIC ALGORITHM FOR U.S. NAVAL MISSION RESOURCE ALLOCATION

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ABSTRACT

Current military leadership is directing the U.S. Navy to engage in theater security cooperation activities or missions to bolster confidence and build trust relationships with other national military forces. Using ships efficiently by maximizing the value of missions accomplished in any time period is important because these missions affect world security, as well as our own national security. Recent research has developed a mixed-integer programming optimization model called Central-West Africa Resource and Mission Allocation (CARMA) that seeks to efficiently route a single naval vessel embarked with expeditionary partnership teams conducting theater security cooperation missions, to maximize the total mission value. The two current algorithms for solving CARMA require commercial software to solve the associated optimization models. This thesis develops a custom-built, license-free heuristic algorithm that provides decent solutions to CARMA in a fraction of the time of these algorithms. The developed heuristic uses limited enumeration to generate feasible routes and mission schedules for the ship. In the scenarios tested, the solution produced by the heuristic is not only generated in a fraction of the time of the current algorithms, but the total mission value collected is within 5% - 7% of those solution values.

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LIST OF ACRONYMS

CARMA	Central-West Africa Resource and Mission Allocation (problem).
CNE-C6F	Commander, Naval Forces Europe-Commander, Sixth Fleet.
CNO	Chief of Naval Operations.
DoD	Department of Defense.
EPT	Expeditionary Partnership Team (analogously, team type).
EUCOM	U.S. European Command.
GAMS	General Algebraic Modeling System.
GFS	Global Fleet Station.
GOG	Gulf of Guinea.
H-CARMA	Central-West Africa Resource and Mission Allocation model Heuristic (algorithm).
HSV	High Speed Vessel.
LR-CARMA	Central-West Africa Resource and Mission Allocation model Linear Relaxation (model).
LSD	Landing Transport Dock Ship.
MIP	Mixed Integer Program.
MIP-CARMA	Central-West Africa Resource and Mission Allocation model Mixed Integer Program (model).
NSS	National Security Strategy.
RH-CARMA	Central-West Africa Resource and Mission Allocation model Rolling Horizon algorithm.
TSC	Theater Security Cooperation.

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EXECUTIVE SUMMARY

Current military leadership is directing the U.S. Navy to engage in theater security cooperation (TSC) activities or missions to bolster confidence and build trust relationships with other national military forces. Building these cooperative, strategic relationships with other nations helps protect U.S. national interests worldwide. However, these critical missions place additional demands on limited U.S. naval assets, so U.S. Navy planners must be selective in managing their limited resources in support of these objectives.

A recent masters' thesis in Optimization Research by Spitz develops a Mixed-Integer Programming (MIP) optimization model called the Central-West Africa Resource and Mission Allocation model (CARMA). CARMA models a logistical problem seeking to efficiently route a naval vessel embarked with multiple types of expeditionary partnership teams (EPTs) to conduct TSC missions in an area of interest, to maximize the total value obtained by completing those missions. CARMA also seeks to optimize the ship's complement of EPTs necessary for completing TSC missions given the ship's limited berthing space. Unfortunately, the full MIP formulation of CARMA (MIP-CARMA) suffers from scalability issues (which result in long run times), and its solution is approximated with a rolling-horizon approach, RH-CARMA. Both MIP-CARMA and RH-CARMA require off-the-shelf commercial optimization software, which complicates its distribution to U.S. Navy end-users.

This thesis develops a custom, license-free, heuristic algorithm, H-CARMA, which solves the above scalability issues and generates high quality solutions for CARMA: H-CARMA can handle much larger cases than RH-CARMA or MIP-CARMA, with longer horizons and/or country and mission sets, and still present a quality solution in less than one minute of computational time.

H-CARMA uses selectively ordered sets and depth-first enumeration with feasibility tests for backtracking to generate feasible routes and mission schedules for the ship. The underlying idea is to extend a partial schedule (comprising a subset of missions

and countries to be visited in a given order) with additional missions, until no more extension is possible. Other refinements, such as a “packing” procedure, ensure that compatible missions (in terms of duration and required EPTs) are also carried out in the country visited by the ship.

Certain restrictions assumed by H-CARMA which are not imposed by CARMA (such as forcing all missions to be performed with the ship staying in port), limit the scope of the algorithm. Despite these restrictions, the results illustrate that H-CARMA performs well compared to known bounds or solutions to CARMA. Specifically, in the scenarios tested, the solution produced by H-CARMA is not only generated in a fraction of the time as compared RH-CARMA, but the TSC values collected are only 5% to 7% below these comparable results. This displays promise for H-CARMA’s future development as a planning tool for use by the U.S. Navy.

I. INTRODUCTION

A. OVERVIEW

Current U.S. foreign policy and its actions in protecting national interests continue to support and encourage globalization. During the last decade, globalization has also brought about a number of security challenges. These include an increase in economic competition for scarce resources, evidence of growing dissatisfaction among those disenfranchised by global trading and the widening regional effects of poorly governed or failing states. In this new global environment, U.S. national security interests are not only far reaching, but also create more demand on our limited resources. In recognition of the challenges this poses on U.S. national security, the U.S. National Security Strategy (NSS, 2006), Defense Strategy (NDS, 2005), and Strategy for Maritime Security (NSMS, 2005) all acknowledge and direct U.S. efforts to build cooperative strategic relationships with other nations to mutually ensure the protection of national interests worldwide.

For the U.S. Navy, building these relationships has become a fundamental requirement in maintaining maritime security and preserving sea power in support of U.S. national interests. Additionally, current military leadership is directing the U.S. Navy to engage in theatre security cooperation (TSC) missions to bolster confidence and build these trust relationships with other national military forces. These critical missions further constrain resources and place additional demands on U.S. naval assets. Success in conducting these missions is directly affected by how well planners can manage their limited resources and negotiate these constraints, among other complications.

This thesis develops a heuristic algorithm which furthers past research to assist planners in routing and scheduling a naval vessel to complete TSC missions given various resource constraints.

B. BACKGROUND

1. A Global Challenge

Increased international and economic trade, the spread and growth of technology and the extension of political and socio-cultural forces across national borders all contribute to what is currently referred to as globalization (Croucher, 2004). Since the Cold War, the U.S. has supported and encouraged free trade and foreign investing which have given rise to economic globalization (Jackson, 2007; Jianyong, 2003). Incorporating this global economic development with the world-shrinking capability of the internet, national and geographical borders become blurred as people around the globe come closer together. While exciting, this new environment also brings new challenges.

The U.S. has been a leader in this expansion of global trade, investment, information, and technology. The resulting phenomenon of globalization now exposes U.S. national interests to new challenges that can threaten national security (NSS, 2006). These new challenges include non-traditional issues such as pandemics, large scale natural disasters, illicit trade as well as other events that degrade social order, encourage crime and corruption or detract from the governing abilities of local authorities. The effects of neglecting these challenges are obvious from past events. From avian influenza to terrorist attacks on America's homeland, many new threats to U.S. national security and national security interests originate far from U.S. physical borders. These new threats not only warrant necessary attention but they also require greater operational reach from existing resources and assets to address them.

The U.S. recognizes that it has limited resources in the face of these additional challenges, and is engaging in the development of partnerships with other nations and organizations to promote national interests and improve security (NSS, 2006). Given the breadth of these interests and the requirements necessary to protect them, establishing these partnerships is not only a critical step in U.S. strategy, but it is also recognition of the fact that building these cooperative partnerships has become a global challenge.

2. Current Doctrine and Policy

From the U.S. White House down to the military service level, current doctrine and policy recognizes the importance of building strategic partnerships as set forth in the U.S. President's 2006 National Security Strategy (NSS) (NSS, 2006). Adding emphasis to this its importance, the National Strategy for Maritime Security, also authored by the President, directly states "the United States supports close cooperation among nations and international organizations…(and)…will continue to promote development of cooperative mechanisms for coordinating regional measures against maritime threats" (NSMS, 2005).

In support of this national focus, the U.S. Department of Defense (DoD) is actively engaged in promoting and integrating operational plans with other nations and multinational agencies to coordinate activities that aid or increase global stability. Former Secretary of Defense, Donald Rumsfeld, stated that "security cooperation also is important for expanding international capacity to meet common security challenges" (NDS, 2005). Additionally, via DoD Directive 3000.05, it is established that these stability operations have the same level of priority as combat operations (DoD 2005). In directing the nation's defense and military initiatives, the DoD establishes clear priorities when considering stability operations with other nations that further mutual security interests. At the service level, the U.S. Navy, Marines and Coast Guard doctrines also echo this same focus and further define how it is to be accomplished.

Stemming from the above strategies, the Navy's Maritime Domain Awareness Concept (MDA, 2007), Cooperative Strategy for 21st Century Seapower (U.S. Seapower 2006), and Naval Operations Concept (NOC, 2006), outline the Navy's role in building these maritime partnerships and cooperative relationships. In summation, all current doctrines not only state that maintaining maritime and national security is a primary mission for U.S. forces, but also indicate that this is to be achieved through security cooperation efforts. For U.S. military personnel, this means "our Sailors and Marines will be critical members of the joint and inter-agency team that interacts with an expanding set of international partners…" (Chief of Naval Operations (CNO), 2006).

In converting this policy to action, U.S. forces continue to conduct missions aimed at bolstering confidence and security among multinational partners. With time, these efforts also build trust and cooperation among these partnered national forces in support of U.S. National strategy (CNO, 2006). For the U.S. Navy, the focus is primarily on maritime security efforts. In support of U.S. strategy, the U.S. Navy's Global Maritime Partnership initiative, aims to achieve this "cooperative approach to maritime security" (CNO et al., 2007) through an expanded network of national and multinational forces. The key focus for the U.S. Navy is that this Global Maritime Partnership initiative can be achieved by building cooperative relationships through theater security cooperation (TSC) activities.

While these cooperative activities are known by a variety of names, this thesis addresses all such activities as *TSC missions*.

3. Theater Security Cooperation Missions

TSC missions are not only fundamental to building cooperative relationships among other national partners, but they also facilitate security efforts directly by increasing overall U.S. presence in other regions of the world. These missions include "capacity-building, humanitarian assistance, regional frameworks for improving maritime governance, and cooperation in enforcing the rule of law in the maritime domain" as well as "military personnel exchange and training programs" (CNO, 2006, 2007). The U.S. hopes to build strong cooperative relationships with other nations through executing these missions. Not only will this allow the U.S. to continue to pursue and protect its vital interests, but it also increases the stability and overall security of volatile regions worldwide.

Spread across the globe, the major unified combatant commands of the DoD have instituted policies and adopted practices in pursuit of establishing these strong relationships and providing security in their areas of interest. For the U.S. European Command (EUCOM), the Gulf of Guinea (GOG) has been primary focus for conducting and planning TSC activities directly (Spitz, 2007). Additionally, the U.S. sub-unified command of Africa, AFRICOM, has adopted TSC activities to build "the capacity of

partner nations, thereby reducing the likelihood of problems developing into crises" (U.S. Africa Commander, 2008). Within each of these commands, the U.S. Navy has the role of focusing on the maritime aspects and navigable waterways to provide security and assistance in these TSC efforts. For EUCOM, the U.S. Naval Forces Europe Sixth Fleet has this responsibility and these efforts have become a top priority for this naval fleet (Spitz, 2007). Additionally, in the U.S. Southern Command, SOUTHCOM, the U.S. Navy recently re-established its Fourth Fleet in the Caribbean, and Central and South America in support of these efforts. CNO Admiral Roughead states:

> Our maritime strategy raises the importance of working with international partners as the basis for global maritime security. This change increases our emphasis in the region on employing naval forces to build confidence and trust among nations through collective maritime security efforts that focus on common threats and mutual interests.
>
> (U.S. Navy, 2008)

As part of its primary mission, this fleet will conduct TSC activities as well as other missions in the region (U.S. Navy Fourth Fleet Commander, 2008).

These initiatives are a primary focus for U.S. military forces. While the objective is building regional relationships among other nations to promote security through these TSC activities, the associated mission tasking may be quite diversified. TSC missions include, but are not limited to, training maritime security forces, building infrastructure, establishing security tactics and practices, and medical training (Spitz, 2007). These TSC operations are aimed at developing cooperative relationships among other nations and, given their variety, they often require new or different resources to complete them.

To conduct TSC operations effectively in various countries, planners must negotiate the needed resources in order to complete these missions and weigh the relative importance of each (Spitz, 2007). Since ship resources are limited, it is likely that the number of missions that can be completed will be limited too. Decision makers must also contend with the natural constraint of time and the availability of personnel able to complete these operations once they are committed to a mission.

4. Current Challenge and CARMA

U.S. Navy decision makers and planners must be selective in how their resources are employed in support of U.S. national security. As noted by Spitz (2007), Navy planners currently use "Effects-Based Thinking" and the specific requests of the hosting nations to incorporate strategic priorities and measures of effectiveness to select missions. There are thousands of options that these planners simply do not have time to consider.

This fundamental challenge has no mathematical models or optimization tools to assist in the planning and scheduling process. Such tools would assist decision makers by presenting routing options in a timely manner while operating within the resource, scheduling and logistical constraints that are inherent in formulating these plans. In recognition of this need, recent research developed a mixed-integer optimization model called the Central-West Africa Resource and Mission Allocation model (CARMA) (Spitz, 2007).

In this thesis, CARMA is refers to the problem to be solved, rather than the mathematical model itself, and MIP-CARMA refers to the mixed-integer programming (MIP) model that Spitz developed to model the CARMA problem.

MIP-CARMA models a logistical problem seeking to efficiently routing a naval vessel embarked with multiple choices of expeditionary partnership teams (EPTs) to conduct TSC missions in an area of interest. Specifically, MIP-CARMA seeks to maximize the total TSC value obtained by completing these missions.

In addition, CARMA also seeks to optimize the ship's complement of EPTs necessary for completing TSC missions given the ship's limited berthing space. The evaluation criterion for choosing among possible schedules and ship configurations is based on two objectives. Every TSC mission is assigned a value and cost once completed. Maximizing the total TSC value collected is the primary determinate for selecting a solution, whereas minimizing total mission (plus port utilization) costs is viewed as a constraint and as a secondary goal, depending on the context.

While this thesis focuses initially on the application of CARMA on the GOG region, this should not be considered a limitation. Both the CARMA problem and the models and algorithms to solve it can be applied to any similar sea-worthy location.

Prior to this research, solving MIP-CARMA (or approximating its optimal solution) required a commercial optimization software license, and the resulting solution procedures exhibited limitations due to scalability. Specifically, Spitz implemented MIP-CARMA in the General Algebraic Modeling System (GAMS) (Brooke et al., 1996) and solved it with GAMS/CPLEX (2008) using formal MIP.

Although CARMA can be characterized as a variant of the “vehicle routing” problem (Toth and Vigo, 2002), the associated models and algorithms need to be rather specific to the nature of the “vehicle,” the route involved and numerous other logistic constraints that further complicate the problem.

The complexity of CARMA creates scalability problems which result in long run times, thus an approximating heuristic method called rolling-horizon (RH-CARMA) was developed (Spitz, 2007). This divides the planning horizon into 30-day segments. As an example, a 90-day schedule would have three 30-day segments. The results of each segment would provide inputs to the following segment. This rolling-horizon process shortens the run time of the full MIP-CARMA, but is also subject to scalability issues (e.g., if more missions or countries were considered), still requires a top-of-the-line commercial MIP optimization engine, and generates a suboptimal solution. In some cases, the resulting solution must undergo post-processing to ensure feasibility, although this is uncommon in practice.

C. PURPOSE

The primary objective of this thesis is to develop a high-quality scalable heuristic algorithm, H-CARMA, that is capable of approximating the optimal solution to MIP-CARMA. An added benefit of this heuristic is its license-free aspect: once developed, this would enable unencumbered distribution for immediate use by U.S. Navy planners.

By focusing on the scalability issue present in the MIP-CARMA and RH-CARMA implementations, H-CARMA is expected to solve larger cases in a fraction of the time. In developing H-CARMA, the mission scenarios and results from the both MIP-CARMA and RH-CARMA are used to validate the heuristic solutions.

To avoid confusion with the heuristic to be developed in this thesis, we will use the following nomenclature: (a) MIP-CARMA refers to the full MIP developed by Spitz, solved using CPLEX (GAMS, 2008); (b) RH-CARMA refers to the rolling-horizon heuristic used by Spitz, which still uses formal MIP to solve each 30-day segment optimally; (c) LR-CARMA, also proposed by Spitz, refers to the linear relaxation of MIP-CARMA, which provides an upper (optimistic) bound on its optimal solution; and, (d) H-CARMA refers to the heuristic algorithm to be developed in this thesis.

The remainder of this document is organized as follows: Chapter II presents the CARMA problem specifications and the modifications made by H-CARMA that differ from MIP-CARMA; Chapter III describes the H-CARMA algorithm; Chapter IV presents an implementation of H-CARMA and compares its performance to RH-CARMA; and Chapter V presents conclusions and recommendations for future research.

II. CARMA PROBLEM AND MODIFICATIONS

This chapter outlines the CARMA problem specifications and any modifications made by H-CARMA that are different from the assumptions used to develop the MIP-CARMA model. Given that a majority of the specifications and assumptions are adopted directly, the reader is encouraged to reference the complete MIP-CARMA formulation by Spitz (2007), as some details will not be fully discussed here.

A. PROBLEM SPECIFICATIONS

CARMA missions are generated by Naval Forces Europe-Commander, Sixth Fleet (CNE,-C6F) as part of an engagement plan to be carried out between 2007 and 2016. These missions must be performed in a set of countries in the GOG, where each mission has a pre-determined TSC value and can be completed by one or more EPTs. Subject to a number of constraints, the basic objective of this problem is to route a Navy vessel equipped with EPTs to these countries to complete missions in order to maximize the total TSC value collected. The information below further outlines the specifications of this problem.

Each of the countries in the GOG has a set of missions. Countries also have a main port that may or may not be able to provide fuel and pr ovisions for the ship. During routing, the ship must stay at or above its minimum fuel level as well as maintain sufficient provisioning supplies for all personnel assigned to the ship. A fixed amount of provisions is consumed every day. The amount of fuel consumed depends on the ship's activity, and two burn rates are used: ship underway (at sea burn rate); and ship anchored or moored at port (in port burn rate). While provisions are measured in terms of days, fuel and fuel burn rates are measured in gallons and gallons/day, respectively. Fuel capacity, burn rates and supply capacity are specific to the type of ship being routed.

A fictitious "At Sea" country represents a port location where the ship may conduct multi-country training missions. Additionally, with the exception of the homeport (Rota, Spain) and the "At Sea" location, the ship incurs a port charge for each day it remains at a port. The port charges vary based on the country in which they are located.

In each country, each mission has a pre-determined TSC value, a cost and a few other attributes. Some missions have a precedence requirement in relation to other missions such that one mission may require one or more mission(s) to be completed before it can be carried out. Every mission requires the ship to deliver an EPT (of potentially multiple types) to the respective country to complete the mission and to also pick up the team immediately upon completion of the mission. Missions have a varying number of days required to complete them. Additionally, some missions may require the ship to stay in port for the duration of the mission. Each mission in each country also has a cost.

For the teams, each EPT is comprised of a number of personnel and collectively has the capability to complete specific missions unique to the particular type of EPT. Each EPT type has a varying number of personnel, and the ship has a limited amount of berthing space (based on ship type) to provide for all the personnel of all EPTs assigned to the ship. EPTs can only complete one mission at a time and are limited in availability based on their type.

B. H-CARMA ROUTING MODIFICATIONS

Most of the assumptions made by the MIP-CARMA model are directly adopted. However, H-CARMA also introduces a number of modifications, which specifically affect ship routing.

1. Mission-Only Routing

Unlike the MIP-CARMA model, in H-CARMA the ship is assumed to route to countries for the sole purpose of conducting missions. In maintaining this focus, the ship is not allowed to route to countries to replenish fuel or supplies without picking up or dropping off a team for a mission. Thus, a number of solutions to the CARMA problem become infeasible as the ship's fuel and provisions resources can only be replenished when accompanied by mission activity at that same country.

2. Homeport Return Not Required

The constraint imposed by MIP-CARMA in forcing the ship to return to its homeport by the end of the planning horizon is not required for H-CARMA. This relaxation allows the routing schedule to remain feasible provided all other constraints are satisfied. Thus, if the ship completes all missions and has collected all outstanding teams in all countries, the associated routing schedule is acceptable. This routing modification inherently assumes that the mission planning horizons are slightly negotiable and extends this benefit to H-CARMA.

3. In Port Mission Assignments

While only some of the missions in CARMA require the ship to remain in port for the duration of the mission, this restriction is extended in H-CARMA to all missions. This assumption, which helps reduce the complexity of the H-CARMA algorithm, restricts the routing of the ship to the respective country in which a mission is taking place.

C. OTHER H-CARMA MODIFICATIONS

A few other assumptions in H-CARMA that do not directly affect the ship's routing (but may render solutions which differ from those by MIP-CARMA) are outlined here.

1. Re-Fueling and Re-Provisioning

While the MIP-CARMA model does not assume that the ship's fuel and supply capacities are replenished to the maximum allowable level when these resources are available in port visited, H-CARMA does. Furthermore, this heuristic assumes that these levels are kept at their respective maximum each and every day the ship is at a port which is capable of providing the associated resource. Since the action of replenishing the ship's resources is cost free, this assumption is not a restriction on the feasible region. In fact, this reduces the complexity of the problem by assuming the ship's fuel and supplies are kept at a maximum at every providing port.

2. Budget Not Minimized

The H-CARMA algorithm maintains a focus on maximizing the total TSC value of a feasible schedule as does MIP-CARMA. However, MIP-CARMA also minimizes the total budget costs after it maximizes the total TSC value (subject to a budget constraint). Since the budget is treated as secondary goal, it is considered to be beyond the scope and purpose of H-CARMA. Thus, in H-CARMA the budget limit is only treated as a constraint and no attempt is made at directly minimizing this goal. Nevertheless, H-CARMA can present the decision maker with a set of plans with similar TSC value, and their associated costs.

3. Scheduling Feasible Missions

Unlike the MIP-CARMA model, where any mission can be added to the schedule on any feasible day, the H-CARMA algorithm assumes these missions can only be added on the earliest day possible in the current schedule. The H-CARMA algorithm assumes that if missions are not feasible on the earliest day possible in the schedule, they cannot be feasibly scheduled at all. This further restricts the feasible region for H-CARMA, but allows solutions to be discovered more quickly.

III. HEURISTIC ALGORITHM

This chapter presents H-CARMA, an enumeration-based heuristic algorithm for solving CARMA, and discusses the algorithm rationale, its development and other implementation details.

A. ENUMERATION OF FEASIBLE SCHEDULES

H-CARMA is based-on depth-first enumeration with backtracking rules that uses a recursive algorithm to enumerate feasible schedules (Kreher and Stinson, 1999). (Hereafter, ship route and schedule are used interchangeably to refer to a time-phased route for the ship, that is, the ports of call and their schedule).

This approach systematically schedules missions to develop feasible ship routes until it has exhausted all feasible permutations of "(mission, country)" pairs, as described later in the chapter. Selective ordering and restrictive backtracking rules reduce the number of (mission, country) pair permutations that H-CARMA considers for placement into a schedule. The number of feasible schedules evaluated by the heuristic is less than the total number of feasible schedules, thus, the heuristic nature of the algorithm. By using limited enumeration, H-CARMA is designed to find high quality solutions while overcoming the scalability issues observed in formal optimization approaches like MIP-CARMA.

Each unique (mission, country) pair becomes the basic element in the schedules developed by H-CARMA. A feasible schedule is defined as sequence of (mission, country) pairs that can be accomplished by routing the ship appropriately. Feasibility is determined by:

- the total time required to execute all scheduled missions
- the daily consumption and/or replenishment of fuel and provisions
- the teams available to conduct each mission at the required time
- the available berthing needed for the teams

- the total cost in executing missions including their associated port costs
- the order in which some of the missions are scheduled (when precedence relationships exist among missions)

Any feasible schedule that does not require the entire time horizon can possibly be extended by adding another (mission, country) pair to the end of that schedule. This can be repeated until the time horizon is exhausted or some feasibility constraint is violated. If this occurs, the last (mission, country) pair must be removed to regain feasibility.

H-CARMA starts with an empty schedule and repeats the above extension process, using backtracking when no further extension can yield a feasible schedule. In generating a large number of feasible schedules, H-CARMA not only retains the one with highest total TSC value, but also presents this schedule to the user as the best one found.

B. ALGORITHM PARAMETERS, DATA AND DECISION VARIABLES

Directly adopted from the MIP-CARMA model by Spitz (2007), a list of original notation for indexed sets, parameters and decision variables is presented here. Additional notation used by H-CARMA is introduced too.

1. Original Sets and Indices

U, EPT type, $u \in U$.

C, countries, $c \in C$. This includes a fictitious country $c_o \in C$ which represents the location "At Sea."

T, time period, $t \in T = \{1,2,...,|T|\}$. Each time period represents one day.

M, missions, $m \in M$.

$J \subset M \times U$,	subset of mission-EPT pairs (m, u) where mission m can be carried out by EPT type u.
$K \subset M \times C$,	subset of mission-country pairs (m,c) where mission m can be carried out in country c.
$B \subset M \times M$,	subset of missions-mission pairs (m, m') where mission m must be carried out before mission m'.
$C^f \subset C$,	subset of countries that can provide fuel.
$C^g \subset C$,	subset of countries that can provide food and water.

2. Original Parameters (units)

$Uracks$,	number of berthing spaces available for EPTs (persons).
np_u ,	number of personnel in EPT type u (persons).
$maxN_u$,	maximum number of EPTs type u that are available (teams).
d_m ,	duration of mission m (days).
tc ,	fuel tank capacity (gal).
$minFuel$,	minimum fuel level allowed (gal).
$initFuel$,	fuel onboard ship at the beginning of day 1 (gal).
b^m,	fuel burn rate when transiting (gal/day).
b^w,	fuel burn rate when in port (gal/day).
$resupplyT$,	maximum time between ship re-supply for food and water (days).
$value_m$,	value earned for accomplishing mission m (value units).
$cost_m$,	cost of mission m (\$).
$pCost_c$,	cost of going in port country c (\$/day in port).
$budget$,	total amount of money allocated for all missions in the region (\$).

3. New Decision Variables, Sets and Parameters

$schedule \subset M \times C$, decision vector, established as an ordered set of mission-country pairs (m,c), where $(m,c) \in K$. This can be interpreted as a partial schedule, which is always kept feasible by H-CARMA.

$bestSolution \subset M \times C$, decision vector: copy of *schedule* for the best incumbent solution found.

$cvalue_c$, country's c potential TSC value, calculated as $cvalue_c = \sum_{m|(m,c) \in K} value_m$.

$list \subset M \times C$, ordered set of mission-country pairs (m,c) where $(m,c) \in K$. This set is explicitly ordered by country TSC value, $cvalue_c$, and then by mission duration, d_m.

$tvalue_u$, team's u potential TSC value calculated as $tvalue_u = \sum_{m|(m,u) \in J} value_m$.

teams, set of EPT types ordered by team value, $tvalue_u$ where $u \in U$.

percentBerthing, percentage of available berthing space (with respect to the total available on the ship, *Uracks*) that the algorithm uses to pre-load the ship.

counterLimit, maximum number of recursive call iterations allowed in H-CARMA, before forcing algorithm termination.

C. H-CARMA ALGORITHM AND PROCEDURES

This section contains the heuristic algorithm and the supporting procedures used to solve the CARMA routing problem. The procedures are presented first to lend better clarity to the enumeration process that takes place in H-CARMA. These procedures include a set of selective ordering routines and the backtracking rules mentioned earlier. The backtracking rules are exclusively contained in the feasibility tests, which comprise a separate routine.

1. Selective Ordering Routines

The selective ordering routines in H-CARMA are executed prior to invoking the enumeration engine of the algorithm. These routines affect how the heuristic algorithm selects (mission, country) pairs and teams as it builds a feasible schedule (represented by the ordered set *schedule*), as well as the initial set of teams that are loaded onto the ship.

a. Ordering of Mission-Country Pairs and Teams

Set *list* has the same number of (mission, country) pairs as set K, expect that in *list* they are ordered hierarchically: first, by country, using the country's total TSC value, $cvalue_c$; second (i.e., for a given country), by mission duration, d_m.

The rationale behind this ordering process is two-fold. First, this allows H-CARMA to use greedy search as the first (mission, country) pairs selected will belong to countries having higher total TSC value. Secondly, the first (mission, country) pair among each subset of pairs will have the longest mission duration. This aids in mission packing (described later in this chapter) which is designed to schedule together as many missions as possible to maximize the total TSC collected in a given country. While this implies that the missions will be completed in groups, it is important to note that H-CARMA evaluates each candidate pair individually before adding it to *schedule*.

Set *teams* is also ordered by a total TSC value, $tvalue_u$. By doing so, H-CARMA establishes a relative importance among the various types of teams it chooses to pre-load on the ship, with the expectation they will complete missions with higher TSC value.

b. Initial Ship Loading

Before H-CARMA adds a (mission, country) pair to *schedule*, it ensures that either a compatible team is already on board or can be added to the ship. To prevent the algorithm from consuming the berthing space with teams having a low relative importance, as determined by set *teams* above, H-CARMA pre-loads the ship with teams to a percentage of the berthing space. This amount of berthing space, or pre-load requirement, is calculated as a percentage (*percentBerthing*) of *Uracks*.

During the pre-loading process, once all available teams of a given type are loaded, H-CARMA advances to the next team type in *teams*. As each team is added, H-CARMA ensures that there is sufficient berthing space available and continues adding teams until the occupied berthing space meets or exceeds the pre-load requirement. If H-CARMA runs out of teams or if the team size exceeds the available berthing space, this loading process stops. Some local parameters are presented below as well as pseudo-code in Figure 1 to help describe this process.

<u>Local Sets, Indices, and Parameters:</u>

P, indexed set $p \in P = \{1, 2, \ldots, |U|\}$ (Note: $|P| = |U| = |teams|$).
u_p, team type, $u \in U$, at position $p \in P$ in *teams*.
L_u, number of teams of type $u \in U$, loaded on ship.
usedSpace, berthing space consumed by current set of teams onboard ship.
reqSpace, required berthing space that must be preloaded with teams.

Initializing Local Parameters:

$$p = 1$$
$$usedSpace = 0$$
$$L_u = 0, \quad \forall u \in U$$
$$reqSpace = percentBerthing \times Uracks$$

Initial Ship Loading Routine (pseudo-code):

While ($usedSpace < reqSpace$ And $p \le |U|$)
  $u = u_p$
  If ($L_u < maxN_u$) then
    If ($usedSpace + np_u$) $< Uracks$ then
      $L_u = L_u + 1$
      $usedSpace = usedSpace + np_u$
    Else
      Exit While
    End if
  Else
    $p = p + 1$
  End if
Loop

Figure 1. H-CARMA Ship Loading Routine.

This Figure shows the pseudo-code used in H-CARMA to initially load the ship with teams. These teams are necessary to complete missions to collect the TSC value associated with each. This is done prior to enumerating through schedules in search of the best one having the highest total TSC value.

A *percentBerthing* value of 70% is used in all of the test cases described in Chapter IV. This value is chosen to allow H-CARMA some flexibility, by balancing the "more important" teams (based exclusively on TSC value) and the potential need to select other teams "on demand" later in the algorithm.

2. Supporting Routines

A few procedures are invoked within the enumeration engine of H-CARMA. These routines are presented here to facilitate better understanding of the ensuing

enumeration process. This does not detract from the importance of these routines as they ensure that the incumbent *schedule* always remains feasible and that H-CARMA terminates when desired.

a. Mission Feasibility

Mission feasibility is evaluated by the *isFeasible((m,c), schedule)* routine in H-CARMA. This evaluation is the most time-intensive part of the H-CARMA algorithm. The *isFeasible((m,c), schedule)* routine ensures that the partial schedule contained in set *schedule*, remains feasible for each added (mission, country) pair during the entire execution of the heuristic.

Recall that each *schedule* is an explicit set of feasible (mission, country) pairs arranged in order of planned completion. Thus, the state of the ship, teams, and overall problem can be derived directly from any given specification of *schedule*. The heuristic starts with *schedule*= ∅ and maintains feasibility by adding a (mission, country) pair that passes the feasibility tests described below. Parameters marked with an asterisk (*) are local results, that is, intermediate calculations:

*earliestDayInSchedule**, earliest day a (mission, country) pair can be added to *schedule*. Note this cannot be earlier than the start day of the last (mission, country) pair added to *schedule*.

*currentFuelLevel**, amount of fuel (gallons) onboard the ship at *earliestDayInSchedule**.

*numberOfDaysInPort**, number of days the ship is in port starting from the *earliestDayInSchedule** to the end of the longest mission duration d_m. Note d_m is determined from the (mission, country) pairs added to *schedule* on or after *earliestDayInSchedule**, and having the same country as the candidate (mission, country) pair.

numberOfDaysAtSea*, number of days at sea the ship spends in traveling from the country of the last (mission, country) pair added to *schedule* to the candidate (mission, country) pair.

daysOfProvisionsLeft*, amount of provisions left (in days) aboard the ship on day *earliestDayInSchedule** (not including this day)

N_u^*, number of teams of type $u \in U$ that are assigned to the ship. Teams assigned to the ship are not necessarily available or onboard the ship at the time a new (mission, country) pair is considered.

M_u^*, number of teams of type $u \in U$ that are on a mission at the time a new (mission, country) pair is considered.

accumCost*, accumulated cost (in dollars) of all missions and port charges up to, but not including *earliestDayInSchedule**.

With the above items calculated from the current *schedule*, for some $(m,c) \in list$, to be added to *schedule*, the following conditions (see items in ( ) in the below pseudo-code) must be true:

- Time – All missions can be completed within the time horizon, $|T|$.

  Let $firstDay = earliestDayInSchedule^*$
  $\left[\, firstDay + d_m \le |T| \,\right]$

- Fuel – The ship's fuel level is at or above the minimum fuel level.

  Let $fuel = currentFuelLevel^*$
  $daysInPort = numberOfDaysInPort^*$
  $daysAtSea = numberOfDaysAtSea^*$
  If $c \notin C^f$ then
  $\left[\, fuel - \left(daysInPort \times b^w + daysAtSea \times b^m\right) \ge minFuel \,\right]$
  End If

- Team Berthing – All team members can be accommodated with ship berthing.

$$\text{Let } usedBerthing = \sum_u np_u \times N_u^*$$
$$\left[usedBerthing \le Uracks \right]$$

- Provisions – The ship has at least 1 day of provisions.

$$\begin{aligned}
&\text{Let } prov = daysOfProvisionsLeft^* \\
&\quad daysInPort = numberOfDaysInPort^* \\
&\quad daysAtSea = numberOfDaysAtSea^* \\
&\text{If } c \notin C^g \text{ then} \\
&\qquad \left[prov - \left(daysInPort + daysAtSea \right) \ge 1 \right] \\
&\text{End If}
\end{aligned}$$

- Budget – The cost of the missions conducted and the total port costs cannot exceed the budget limit.

$$\begin{aligned}
&\text{Given an } (m,c) \in list, \text{ considered for } schedule, \\
&\text{Let } daysInPort = numberOfDaysInPort^* \\
&\left[accumCost^* + daysInPort \times pCost_c + cost_m \le budget \right]
\end{aligned}$$

- Precedence – Any mission with precedence cannot be feasibly scheduled until all specified precedent missions are completed first.

$$\begin{aligned}
&\text{If } \left(m,c\right),\left(m',c'\right) \in schedule \text{ And } (m,m') \in B \text{ then} \\
&\qquad \left[\text{finish time for } m < \text{ start time for } m' \right] \\
&\text{End if}
\end{aligned}$$

- Team Availability – There must be a team either onboard the ship or one that can be added to the ship that is capable of completing the mission. Note if a team is added to the ship, sufficient berthing

space must be available as well. The pseudo-code in Figure 2 below illustrates this concept.

Let $usedBerthing = \sum_u np_u \times N_u^*$

$teamFound = false$

For Each $u \in teams \,|\, (m,u) \in J$

  If $N_u^* - M_u^* \geq 1$ then

    $M_u^* = M_u^* + 1$

    $[teamFound = true]$

  Else If $maxN_u > N_u^*$ then

    If $(usedBerthing + np_u) \leq Uracks$ then

      $N_u^* = N_u^* + 1$

      $M_u^* = M_u^* + 1$

      $usedBerthing = \sum_u np_u \times N_u^*$

      $[teamFound = true]$

    End If

  End If

Next u $(\text{until } teamFound = true)$

Figure 2. H-CARMA Feasibility Test for Team Availability.

This Figure shows the pseudo-code used in H-CARMA to check for available teams to carry-out missions. A team capable of completing a given mission must be available on the ship or can be feasibly added to the ship for the mission to be considered feasible.

Based on the above feasibility conditions, only feasible (mission, country) pairs that keep the *schedule* feasible can be added to form a new feasible *schedule*. Each time a (mission, country) is added, the associated (m,c) pair is placed at the end of this ordered set, such that the new set can be expressed as $schedule = \{schedule, (m,c)\}$.

b. Mission Packing

Mission packing is a procedure implemented as a nested loop that executes after a (mission, country) pair is added to *schedule*. The purpose of mission packing is to accelerate the formation of multiple schedules by having H-CARMA schedule other (mission, country) pairs concurrently. Once H-CARMA makes its first selection, it records the country associated to the (mission, country) pair as *Cstart*, and the mission duration as $d_{m,\,first}$. Other (mission, country) pairs having the same country *c=Cstart*, and having less or equal mission duration, $d_m \le d_{m,\,first}$, are also considered for *schedule.*

Based on the assumptions presented earlier, all missions require the ship to stay in port for the entire mission duration. Therefore, once the first (mission, country) pair is selected, the country is known as well as the fuel, provisions and time consumed as the ship waits in port. The mission packing loop then considers other feasible missions that meet the criteria above for possible addition to the current *schedule*.

Cstart and $d_{m,\,first}$ as used above are control variables. They each record the country and mission duration, respectively, of the associated (mission, country) pair added to *schedule* prior to the mission packing loop. These variables are then used to filter out other (mission, country) pairs selections and effectively reduce the H-CARMA's feasible region. Pseudo-code implementing this concept in Figure 3 is outlined here:

For each $(m,c) \in list \,|\, (m,c) \notin schedule, c = Cstart$

  If $d_m \le d_{m,\,first}$

    If *isFeasible((m,c), schedule)*

      $schedule = \{schedule, (m,c)\}$

    End If

  End If

Next (*m,c*)

Figure 3. H-CARMA Mission Packing Routine.

This Figure shows the pseudo-code used in H-CARMA to concurrently schedule missions have equal or less duration and in the same country as a prior selected mission in the associated (mission, country) pair. This is an embedded routing in the H-CARMA enumeration algorithm.

Thus, each (mission, country) pair not already in *schedule* and having the same country as *Cstart* is considered in the mission packing loop. If this pair also has equal (or less) mission duration, $d_m \le d_{m,\,first}$, and passes the other feasibility tests, it is added to *schedule*.

c. Updating the Best Solution

Anytime H-CARMA is forced to remove a (mission, country) pair to regain feasibility and continue the enumeration process, it evaluates the current schedule. The routine *updateBestSolution(schedule)* calculates the total TSC for the current specification of *schedule* and compares it to the incumbent best schedule, *bestSolution*. Before the last (mission, country) pair added to *schedule* is removed in search of other scheduling possibilities, H-CARMA updates *bestSolution* if the current *schedule* has a higher total TSC value. The pseudo-code below illustrates this concept:

$$\text{If} \sum_{\substack{(m,c)\in \\ schedule}} value_m \;>\; \sum_{\substack{(m,c)\in \\ bestSolution}} value_m \;\text{ then}$$

$$bestSolution = schedule$$

End If

In addition to keeping track of bestSolution as shown, H-CARMA also maintains a set of schedules with their associated TSC value and cost. This is provided to the decision maker in order to illustrate the trade-offs between cost and total TSC among the schedules found so a more informed decision can be made.

3. Initializing H-CARMA

Prior to executing the enumeration in H-CARMA, a few parameters are set to initialize the algorithm. While the parameters in each section below can be initialized at once, they are separated here to clarify the part of the algorithm in which they are needed.

a. H-CARMA Enumeration

$Cstart = \text{(empty)}$, country associated to the incumbent (mission, country) pair added to *schedule*.

$counter = 0,$ iteration counter of recursive calls in the algorithm (forces program termination when $counter > counterLimit$).

$d_{m,\,first} = 0,$ duration of mission, *m* for country, *c* belonging to the first (mission, country) pair added to *schedule* before the mission packing loop is executed.

b. IsFeasible() Routine

A few parameters must be made available to the *isFeasible()* routine in order to test for feasibility. Initially, for the empty *schedule* set, the following values are applicable:

$t = 2,$ first possible day when a mission can be added (ship spends the first day in its homeport).

initFuel = tc, the ship starts with a fuel tank of fuel.

prov = resupplyT, the ship starts with a full supply of food and water.

4. The H-CARMA Algorithm

With the parameters, data and supporting procedures established above, the H-CARMA algorithm is initialized and enumerates through the (mission, country) pairs evaluating feasible (possibly partial) schedules in search of a better solution. The algorithm is outlined in Figure 4 as follows:

H-CARMA (*schedule*)

```
{
    For each (m,c) ∈ list | (m,c) ∉ schedule
        If isFeasible((m,c), schedule)
            schedule = {schedule, (m,c)}
            Cstart = c
            d_{m, first} = d_m
(Begin mission packing) →   For each (m′,c′) ∈ list | (m′,c′) ∉ schedule , c = Cstart
                If d_m ≤ d_{m, first}
                    If isFeasible( (m′,c′) , schedule)
                        schedule = {schedule, (m′,c′)}
                    End If
                End If
            Next (m′,c′)
            If counter < counterLimit,
                counter = counter + 1
                HCARMA (schedule)
            Else
                Output bestSolution
            End If
        End If
    Next (m,c)
    updateBestSolution(schedule)
}
```

End H-CARMA

Figure 4. H-CARMA Enumeration Routine.

This Figure shows the pseudo-code used in H-CARMA to enumerate through (mission, country) pairs to explore and test multiple schedules based on the total TSC values collected. The enumeration is carried out by using a recursive call and the best schedule is retained to display to the user when the program terminates.

5. Discussion

H-CARMA starts with *schedule*=∅ and repeats the extension process described earlier by trying to add new feasible (mission, country) pairs to this set. Using selective ordering and backtracking rules to reduce the number of permutations considered, H-CARMA generates a large number of feasible schedules and retains the one with the highest TSC value.

H-CARMA also takes full advantage of recursion to enable the enumeration process to create new feasible values for *schedule* by extending each incumbent one. While recursion enables the enumeration of (mission, country) pairs to form new schedules, other features of H-CARMA reduce the feasible region. These features, which include the *isFeasible()* routine, mission packing, and the iteration counter, focus on keeping the incumbent *schedule* set feasible, and strive to overcome the scalability challenge while still seeking a high quality solution.

a. Use of Recursive Calls

During execution of the heuristic algorithm, each recursive call invokes the algorithm (creating copies of itself) to search for a new feasible (mission, country) pair to add to *schedule*. While not meant to fully describe recursion, the following should provide enough insight to understand how H-CARMA enumerates through the feasible schedules.

Over the course of the algorithm's execution, the virtual copies form a "stack" as one invokes the other and passes on an incumbent specification for *schedule*, and the current country, *Cstart*. While every previous virtual copy retains the schedule information prior to the addition of a new (mission, country) pair, each invoked copy in this stack has an extended feasible *schedule.* The last invoked copy may not have an extended schedule as it is the one searching for a new feasible (mission, country) pair. This makes enumeration possible as each invoked copy retains a "memory" of the preceding *schedule* prior to each (mission, country) added. Thus, every copy or level in the virtual stack, inherently knows where the last (mission, country) pair was added and

what other pairs already exist on the current *schedule*. When the algorithm cannot add a feasible pair to the current *schedule*, it naturally returns to the previous copy that invoked the incumbent search. Thus, every *schedule* in each previous copy in the stack is potentially smaller than those contained in the copies it invokes. From these earlier copies, the algorithm picks up its search from where it left off and continues looking for more (mission, country) pairs it can add to the schedule found in that copy.

b. Maintaining Feasibility

All feasible solutions found by H-CARMA are a subset of the solutions contained in the feasible region of the CARMA problem. As its name indicates, the *isFeasible()* routine keeps *schedule* feasible throughout H-CARMA's execution. This routine implements the assumptions made earlier in Chapter II and, therefore, entails a restriction on the feasible region of the CARMA problem.

c. Scheduling Missions Together

To assist H-CARMA in finding a solution quickly, (mission, country) pairs are packed together every time a new selection is made in the outer for loop of the H-CARMA algorithm (see section III.C.4). This process, termed "mission packing," is implemented in the inner for-loop so denoted in the above pseudo-code. Mission packing presents a restriction on the feasible region because it reduces the number of permutations available for enumeration. Each recursive call now potentially schedules (mission, country) pairs in groups, not individually. While this restriction may not be entirely desirable, scheduling in groups of missions increases the speed of the algorithm. Additionally, with the (mission, country) pairs and teams in their selectable ordered sets, the selections made by the mission packing loop tend to maximize TSC value and hopefully mitigate the overall impact of that restriction on the feasible region explored.

d. Iteration Counter

The use of *counter* and *counterLimit* limits the number of iterations in the enumeration process. This forces H-CARMA to terminate early and present its best known solution found. This, too, poses a restriction on the explored feasible region

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IV. IMPLEMENTATION AND RESULTS

This chapter describes the implementation and results of the H-CARMA heuristic. The results are used to compare H-CARMA to MIP-CARMA, which uses formal optimization to solve the problem as a MIP, and includes the RH-CARMA heuristic and the LR-CARMA relaxation, where appropriate.

The results generated from these models and heuristics come from a set of missions previously defined by CNE-C6F for their 2007 GOG Global Fleet Station (GFS) Demonstration, as consolidated in a number of scenarios developed by Spitz (2007), who also implemented MIP-CARMA. These results are used to measure the relative performance of the H-CARMA heuristic, including solution quality and scalability.

H-CARMA is implemented in Visual Basic for Applications and uses Microsoft Office Excel 2003 for an interface (Microsoft, 2008), on a Pentium Celeron with 448 MB of memory and at a speed of 1.5GHz.

A. SCENARIO DATA

All data comes from the 2007 GOG GFS Demonstration developed by the CNE-C6F GOG Regional Planning Team (Spitz, 2007). The author had access to most of the mission data used by Spitz, except for three missions. In order to properly compare results, MIP-CARMA was re-run for all of the scenarios without those missions.

In addition, Senegal, which is a logistics port, has been assigned one mission with a TSC value of one. This mission is designated for the purpose of refueling and resupply and is assigned non-zero value to provide visibility to the heuristic.

Table 1 contains information about the two ships, a landing transport dock ship (LSD) and a high speed vessel (HSV) that will be used in the test cases. Tables 2-4 contain some of the team, (mission, country) pairs and mission specifics, respectively, for these scenarios.

Ship Type	Berthing Capacity (people)	Fuel Tank Capacity (gal)	Minimum Fuel		Burn Rates	
			(gal)	(%)	Underway (gal/day)	In Port (gal/day)
LSD	454	804,300	482,580	60%	12,902	4,173
HSV	107	138,600	34,650	25%	8,316	2,772

Table 1. LSD and HSV Ship Characteristics.

Team Type (name)	Total Available (#)	Size of Each Team (# of people)
ship	3	1
uscg1	2	4
eod	3	12
ncf	4	13
mcag	2	6
etc	4	4
mesf	4	24
exmed	2	5
otherRes	2	4
mda	2	4

Table 2. Team Availability and Size.

CARMA GOG MISSIONS / ACTIVITIES	Countries in GOG							
	GHANA	GABON	STP	CAMEROON	ANGOLA	LIBERIA	ATSEA	SENEGAL
MEDICAL								
MEDICAL OPS/READINESS	x		x					
HA/DR OF INFECTIOUS DISEASES	x							
INFRASTRUCTURE								
ENG RECONSTRUCTION SMEE, DIG WELLS	x	x	x	x		x		
RENOVATE MEDICAL CLINICS		x	x					
RENOVATE SCHOOLS / YOUTH ORGANIZATION CLINICS		x	x					
AIRPORT INFRASTRUCTURE IMPROVEMENTS	x							
ROAD IMPROVEMENTS	x	x	x	x				
UTILITY IMPROVEMENTS	x	x	x	x				
PORT INFRASTRUCTURE IMPROVEMENTS						x		
INFRASTRUCUTRE GAP ANALYSIS	x	x	x	x				
CIVIL / COMMUNICATIONS								
PUBLIC AFFAIRS SMEE	x	x	x	x	x	x		
BAND LESSONS	x	x	x	x				
COMREL					x	x		
SURFACE MARITIME ACTIVITIES								
PORT SECURITY MTT	x					x		
MULTINATIONAL EXERCISE							x	
SHIPRIDER EMBARKS							x	
SMALL BOAT / BOAT PATROL MAINTENANCE MTT	x		x					
ISPS ASSIST / CERT VISIT	x	x	x	x				
HYDRO SURVEY MTT	x		x					
MINE CLEARANCE					x			
MILITARY & LEADERSHIP TRAINING								
COMMUNICATIONS MTT	x	x		x				
OFFICER LEADERSHIP MTT	x			x				
NCO PROFESSIONAL DEVELOPMENT SMEE/ MTT	x							
MARITIME DOMAIN AWARENESS ACTIVITIES								
SHIP VISIT					x	x		
MDA SITE SURVEY								
AIS RECEIVER SITES CONSTRUCTED	x		x			x		
COOPERATIVE SECURITY LOCATION	x							
GFS DEMO							x	
GFS DEMO 2							x	
LOGISTICS								
LOGISTICS STOP								x

Table 3. All Mission–Country Pairs.

CARMA - GOG MISSIONS / ACTIVITIES	Duration (days)	Cost ($) / mission	TSC value
MEDICAL			
MEDICAL OPS/READINESS	5	$5,000	3
HA/DR OF INFECTIOUS DISEASES	3	$7,500	4
INFRASTRUCTURE			
ENG RECONSTRUCTION SMEE, DIG WELLS	10	$65,000	5
RENOVATE MEDICAL CLINICS	3	$10,500	2
RENOVATE SCHOOLS / YOUTH ORGANIZATION CLINICS	3	$10,500	2
AIRPORT INFRASTRUCTURE IMPROVEMENTS	15	$97,500	6
ROAD IMPROVEMENTS	10	$6,500	4
UTILITY IMPROVEMENTS	10	$6,500	5
PORT INFRASTRUCTURE IMPROVEMENTS	20	$13,000	9
INFRASTRUCUTRE GAP ANALYSIS	5	$32,500	5
CIVIL / COMMUNICATIONS			
PUBLIC AFFAIRS SMEE	3	$9,000	5
BAND LESSONS	2	$4,000	1
COMREL	2	$1,000	3
SURFACE MARITIME ACTIVITIES			
PORT SECURITY MTT	5	$45,000	8
MULTINATIONAL EXERCISE	5	$2,500	10
SHIPRIDER EMBARKS	5	$2,500	7
SMALL BOAT / BOAT PATROL MAINTENANCE MTT	5	$7,500	6
ISPS ASSIST / CERT VISIT	10	$20,000	8
HYDRO SURVEY MTT	10	$20,000	8
MINE CLEARANCE	10	$60,000	7
MILITARY & LEADERSHIP TRAINING			
COMMUNICATIONS MTT	5	$10,000	4
OFFICER LEADERSHIP MTT	5	$7,500	7
NCO PROFESSIONAL DEVELOPMENT SMEE/ MTT	3	$1,500	6
MARITIME DOMAIN AWARENESS ACTIVITIES			
SHIP VISIT	5	$2,500	5
MDA SITE SURVEY	5	$10,000	7
AIS RECEIVER SITES CONSTRUCTED	10	$65,000	9
COOPERATIVE SECURITY LOCATION	5	$10,000	10
GFS DEMO	3	$6,000	7
GFS DEMO 2	2	$4,000	7
LOGISTICS			
LOGISTICS STOP	1	$500	1

Table 4. Mission Attributes.

Attributes for the missions defined in CARMA by CNE-C6F (except TSC value, which was subjectively assigned by Spitz). Each mission shown may be performed in one or more countries (see Table 3).

B. H-CARMA SCENARIOS AND RESULTS

Due to the fact that the MIP-CARMA optimization model maximizes the total TSC value and then minimizes cost, not all of the scenarios developed by Spitz can be solved with the H-CARMA heuristic. As such, the reader is encouraged to reference the development of these scenarios in Spitz's work as those that are considered applicable here are briefly reviewed.

It is also important to review how MIP-CARMA is implemented to solve this problem. MIP-CARMA has difficulty with scalability, that is, the size of the MIP optimization model developed to represent the CARMA problem. For the 180-day time horizon, MIP-CARMA cannot produce a solution in an acceptable time frame. Even for the 90-day time horizon, this model may run for several hours without producing a solution. To remedy this issue, Spitz uses RH-CARMA, a rolling-horizon algorithm that applies MIP-CARMA in 30-day increments, as discussed in section I.C. Being a heuristic, RH-CARMA is bound by a relaxation of MIP-CARMA, called LR-CARMA. This provides a bound for RH-CARMA (or any other heuristic). H-CARMA results are compared to RH-CARMA and LR-CARMA, as appropriate.

All of the scenarios have a \$10 million budget limit, a maximum supply limit of 25 days, and (unless otherwise noted) are solved by H-CARMA limited by $counterLimit = 100{,}000$ iterations.

1. Scenario 1: 2007 GOG Six-month Demonstration

This scenario is a direct reflection of the planned deployment by CNE-C6F for the GFS Demonstration in 2007. The specific mission activities selected by CNE-C6F's planning group come from their 2006 unclassified war-game (Spitz, 2007). In this scenario, a LSD is routed throughout the GOG region over a 180-day period to complete 66 missions.

a. Results

Table 5 shows the route and missions selected by H-CARMA for the first days of the horizon. As expected, the ship sails to Ghana as it has the highest total TSC value and is ordered first by the selective ordering in the heuristic. Additionally, we observe the effects of mission packing: H-CARMA selects the “Airport infrastructure improvements” mission in Ghana to start on day 10, and then schedules a number of other missions with shorter duration in parallel, in the same country. This is repeated with the “AIS receiver sites constructed” mission on day 25 as well. H-CARMA systematically, selects a mission, attempts to package other missions together, schedules these missions as a group, and then advances time to repeat this process throughout the schedule.

H-CARMA keeps the ship fully fueled and provisioned every day it is in Ghana. Thus, not only does the algorithm schedule all the missions for completion in this time block, but it also shows the ship leaving Ghana with a full tank of fuel and a full supply of food and water. Since H-CARMA concentrates on keeping the schedule feasible, it does not specify an exact day when refueling or resupply takes place. In Table 6, 24 days elapse between resupply times for the ship. This shows that H-CARMA does utilize the amount of supplies and fuel on board to maximize the ship’s time spent in countries that do not provide refueling or resupply opportunities. (While this ship can carry up to 30 days of provisions, a maximum of 25 days is used as a conservative value for these scenarios in order to compensate for possible spoilage.)

<table>
<tr><td></td><td>MISSIONS</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td></tr>
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Table 5. H-CARMA Developed Schedule for Days 1-34 in the 2007 GOG Six-month Demonstration.

This table illustrates the routing plan for a LSD ship and the missions to be accomplished in the GOG for days 1-34. The team types conducting the missions are shaded above for the respective mission type and time period for each scheduled mission. * denotes countries that provide fuel and supplies.

Tables 6-8 show evidence that H-CARMA eliminates missions from the schedule. This is primarily due to the budget constraint which approaches the limit of $10 million, as shown in the performance tables later. The in port assumption made by H-CARMA is the likely cause as costs are incurred every day the ship stays in a port. While minimizing cost is outside of the focus of the heuristic, its impact on maximizing the total TSC value is evident based on the missions H-CARMA does not schedule.

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<tr><th></th><th>MISSIONS</th><th>35</th><th>36</th><th>37</th><th>38</th><th>39</th><th>40</th><th>41</th><th>42</th><th>43</th><th>44</th><th>45</th><th>46</th><th>47</th><th>48</th><th>49</th><th>50</th><th>51</th><th>52</th><th>53</th><th>54</th><th>55</th><th>56</th><th>57</th><th>58</th><th>59</th><th>60</th><th>61</th><th>62</th><th>63</th><th>64</th><th>65</th><th>66</th><th>67</th><th>68</th></tr>
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Table 6. H-CARMA Developed Schedule for Days 35-68 in the 2007 GOG Six-month Demonstration.

This table illustrates the routing plan for a LSD ship and the missions to be accomplished in the GOG for days 34-68. This schedule shows a few missions that H-CARMA does not schedule in Gabon due to resource constraints (those not scheduled in Cameroon are scheduled later). The team types conducting the missions are shaded above for the respective mission type and time period for each scheduled mission. * denotes countries that provide fuel and supplies.

While it appears that Cameroon only has one mission scheduled for five days in Table 6, the algorithm does not neglect the other missions that last fewer days. Rather, it schedules them later (see Table 7). On day 53, all teams are onboard excluding the one team conducting a mission. Therefore, other teams are available who could be employed to do other missions like band lessons and

public affairs which are both less than five days. However, since the algorithm adds these missions later, this becomes a matter of preference and does not affect the algorithm's performance. (Ultimately, these decisions are left to ship captains and fleet planners as to which option seems to better meet the needs of the crew and objectives at the time.)

	MISSIONS	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY						CAMEROON					UNDERWAY			AT SEA				UNDERWAY		LIBERIA		UNDERWAY		SENEGAL*	UNDERWAY	
	UNDERWAY																											
CAMEROON	ENG RECONSTRUCTION SMEE, DIG WELLS							NCF																				
CAMEROON	ROAD IMPROVEMENTS							NCF																				
CAMEROON	UTILITY IMPROVEMENTS							NCF																				
CAMEROON	INFRASTRUCUTRE GAP ANALYSIS				NCF																							
CAMEROON	PUBLIC AFFAIRS SMEE			MCAG																								
CAMEROON	BAND LESSONS		oth.RES																									
CAMEROON	ISPS ASSIST / CERT VISIT							USCG1																				
CAMEROON	COMMUNICATIONS MTT																											
CAMEROON	OFFICER LEADERSHIP MTT				SHIP																							
AT SEA	MULTINATIONAL EXERCISE															SHIP												
AT SEA	SHIPRIDER EMBARKS															SHIP												
AT SEA	GFS DEMO														SHIP													
AT SEA	GFS DEMO 2													MDA														
LIBERIA	ENG RECONSTRUCTION SMEE, DIG WELLS																											
LIBERIA	PORT INFRASTRUCTURE IMPROVEMENTS																											
LIBERIA	PUBLIC AFFAIRS SMEE																											
LIBERIA	COMREL																					SHIP						
LIBERIA	PORT SECURITY MTT																											
LIBERIA	SHIP VISIT																											
LIBERIA	AIS RECEIVER SITES CONSTRUCTED																											
SENEGAL*	LOGISTICS STOP																									log1		

Table 7. H-CARMA Developed Schedule for Days 69-95 in the 2007 GOG Six-month Demonstration.

This table illustrates the routing plan for a LSD ship and the missions to be accomplished in the GOG for days 69-95. The team types conducting the missions are shaded above for the respective mission type and time period for each scheduled mission. * denotes countries that provide fuel and supplies.

In Table 7, the supply constraint again appears to have a strong affect. After completing the "At Sea" missions, H-CARMA selects a two-day mission in Liberia. This stretches out the 25 days of supplies the ship has onboard before it must resupply in

Senegal. While it may not be realistic for the ship to make a stop for this one mission to be accomplished by itself, the algorithm demonstrates its ability to maximize TSC value in utilizing all available days before being force to resupply the ship. A more realistic alternative might be to schedule this mission with the others on day 96 (Table 8). In either case, H-CARMA demonstrates its usefulness as a planning tool and its capability to effectively handle scalability and find a quality solution.

	MISSIONS	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT					LIBERIA								UNDERWAY				ANGOLA										
	UNDERWAY																											
LIBERIA	ENG RECONSTRUCTION SMEE, DIG WELLS					NCF																						
LIBERIA	PORT INFRASTRUCTURE IMPROVEMENTS																											
LIBERIA	PUBLIC AFFAIRS SMEE		MCAG																									
LIBERIA	COMREL																											
LIBERIA	PORT SECURITY MTT			MESF																								
LIBERIA	SHIP VISIT			SHIP																								
LIBERIA	AIS RECEIVER SITES CONSTRUCTED					NCF																						
ANGOLA	PUBLIC AFFAIRS SMEE																	MCAG										
ANGOLA	COMREL																SHIP											
ANGOLA	MINE CLEARANCE																											
ANGOLA	SHIP VISIT																											

Table 8. H-CARMA Developed Schedule for Days 96-122 in the 2007 GOG Six-month Demonstration.

This table completes the 180 day routing plan of a LSD ship for this scenario. H-CARMA completes the 180 day routing schedule by day 113. Due to the heuristic's constraints, this shows the last of the 61 missions H-CARMA is able to complete. The team types conducting the missions are shaded above for the respective mission type and time period for each scheduled mission.

The routing schedule is completed by day 113 of the 180-day time horizon (see Table 8). Although H-CARMA has enough time in the time horizon to complete all the missions, it only completes 61 of the 66 missions available. A closer look at the constraints of this problem provides some insight into this issue. The algorithm accrues $9.9 million in costs while constructing this schedule which is very near its $10 million budget limit. This cost could not be avoided due to the all in port mission assumption in H-CARMA.

b. Performance

Overall, H-CARMA performs very well as compared to RH-CARMA and LR-CARMA. This is somewhat surprising given the number of feasibility restrictions in H-CARMA. Based on the TSC values and the number of iterations needed to obtain this solution quality, as seen in Tables 9-10, H-CARMA not only handles scalability well, but also finds a solution that is only 7% below optimal (obtained by RH-CARMA, as proved by bound comparison with LR-CARMA). The five missions H-CARMA cannot schedule would violate the budget limit, due to the simplification made by H-CARMA regarding in port-only missions.

Model or Algorithm	TSC	% of LR-CARMA	# of Missions Completed
LR-CARMA	348	100%	66
RH-CARMA	348	100%	66
H-CARMA	323	93%	61

Table 9. H-CARMA Solution Performance for GOG Six-month Demonstration.
This table shows the comparison of H-CARMA's performance to the rolling horizon Heuristic RH-CARMA and its linear relaxation LR-CARMA. Results are based on 100,000 iterations in H-CARMA, the LSD Ship, and scenario data provided by CNE-C6F for the Six-month Demonstration.

Table 10 contains the results from H-CARMA based on the number of iterations the heuristic is allowed. H-CARMA reaches its best result in 50,000 iterations and less than one minute, as compared to RH-CARMA which completes in just under 23 minutes.

H-CARMA Performance for LSD 180 Day Routing Schedule			
Iterations	TSC	Cost ($)	# of Missions Completed
1,000,000	323	$9,924,500	61
100,000	323	$9,924,500	61
50,000	323	$9,924,500	61
10,000	314	$9,955,500	60

Table 10. H-CARMA Iteration Performance for GOG Six-month Demonstration.
This table shows the H-CARMA's performance based on number of iterations run. Best TSC value of 323 is reached at 50,000 iterations which occurs in under one minute of computational time.

While the port cost seems to be a binding constraint, the team configuration does not. Note from Table 11 that only 72% of the berthing space is utilized to complete the 61 missions. This leaves 129 berthing spaces available which suffices for any team or number of teams to be added to the ship from the data in Table 2. It is also interesting to point out H-CARMA's pre-loading routine that adds the teams to the ship (using 70% of the berthing space available), may not be desired. As seen in Table 11, and in the schedules produced, some of these teams, e.g., "eod" and "nwc," may never be used. Of course, this is resolved by a straightforward post-processing of the solution which selects the teams which are required in the final schedule.

Team type	#
ship	3
uscg1	2
nwc	4
eod	1
navelsg	0
ncf	4
comcam	0
riverine	0
mcag	2
etc	4
mesf	4
exmed	2
otherRes	2
mda	2
Total Berthing Used	**325**
	72%

Table 11. LSD Ship Complement: H-CARMA Teams Loaded on LSD for 180-day Schedule in GOG.

This table shows the teams loaded on a LSD ship. Of the 454 berthing spaces available, H-CARMA only consumes 325 spaces (72%) to complete 61 of 66 missions possible for a total TSC value of 323 (with 348 being the total possible).

2. Scenario 2: GOG 90-Day Demonstration

This scenario is directly analogous to the above except that it imposes a more restrictive planning horizon of 90 days.

a. Results

Based on the schedules developed by H-CARMA for the 180-day, Scenario 1, the first 80 days are identical. The only differences appear towards the end of the schedule as shown in Table 12. This is not surprising as the enumeration process is limited to the number of iterations it can perform, which limits the number of feasible schedules H-CARMA can generate. By using recursive calls, H-CARMA removes (mission, country) pairs towards the end of the schedule.

In comparing with Scenario 1, Senegal is no longer scheduled and Gabon becomes the refueling and logistics stop for the ship. Additionally the "At Sea" missions are still scheduled as a group; however, this group is scheduled later than it was previously in the 180-day schedule. Thus, both enumeration and the mission packing routines are working together as designed.

<table>
<tr><th></th><th>MISSIONS</th><th>69</th><th>70</th><th>71</th><th>72</th><th>73</th><th>74</th><th>75</th><th>76</th><th>77</th><th>78</th><th>79</th><th>80</th><th>81</th><th>82</th><th>83</th><th>84</th><th>85</th><th>86</th><th>87</th><th>88</th><th>89</th><th>90</th></tr>
<tr><td></td><td>SHIP LOCATION
EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT</td><td>UNDERWAY</td><td colspan="10">CAMEROON</td><td>UNDERWAY</td><td colspan="3">GABON*</td><td>UNDERWAY</td><td colspan="5">AT SEA</td><td></td></tr>
<tr><td></td><td>UNDERWAY</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="9">CAMEROON</td><td>ENG RECONSTRUCTION SMEE, DIG WELLS</td><td></td><td colspan="10">NCF</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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Table 12. H-CARMA Developed Schedule for Days 69-90 in the GOG 90-day Demonstration.

This table illustrates the routing plan for a LSD ship and the missions to be accomplished in the GOG for days 69-90. (The first 80 days of this schedule are identical to the 180-day schedule for the GOG six-month demonstration, see Tables 5-6.) This schedule shows evidence of the enumeration process in H-CARMA during the last 10 days of routing. The team types conducting the missions are shaded above for the respective mission type and time period for each mission. * denotes countries that provide fuel and supplies.

b. Performance

From Table 13, H-CARMA achieves 81% of the LR-CARMA upper bound in this scenario, and is still only 7% below the feasible solution achieved by RH-CARMA. Due to the tighter time constraint of 90 days, neither heuristic can complete all 66 missions. While RH-CARMA is able to complete 56 missions, H-CARMA completes 54. This also indicates that H-CARMA is still performing comparatively well given this shorter time horizon.

Model or Algorithm	TSC	% of LR-CARMA	# of Missions Completed
LR-CARMA	348	100%	66
RH-CARMA	305	88%	56
H-CARMA	283	81%	54

Table 13. H-CARMA Solution Performance for GOG 90-Day Demonstration.
This table shows the comparison of H-CARMA's performance to rolling horizon Heuristic RH-CARMA and its linear relaxation LR-CARMA. Results are based on 100,000 iterations in H-CARMA, the LSD Ship, and scenario data provided by CNE-C6F for the 90-day Demonstration.

The ship configuration for the 90-day schedule is identical to Table 11 from the previous scenario. This is expected since the ship types are the same. However, this also implies that, like the 180-day scenario, team availability is not a limiting factor. Recall from Table 11, that only 72% of the berthing space is used. Additionally, the total cost incurred from this 90-day schedule is $1.8 million below the budget limit (see Table 14). Therefore, in this scenario, the time constraint of 90 days is the most influential constraint that challenges both heuristics in maximizing total TSC. Given the fact that H-CARMA performs at least as good as it did in the first scenario, the results here further support this algorithm's capabilities and potential.

H-CARMA Performance for LSD 90 Day Routing Schedule			
Iterations	TSC	Cost ($)	# of Missions Completed
1,000,000	283	$8,152,500	54
100,000	283	$8,152,500	54
50,000	283	$8,152,500	54
10,000	283	$8,152,500	54

Table 14. H-CARMA Iteration Performance for GOG 90-Day Demonstration.
This table shows H-CARMA's performance based on number of iterations run. Best TSC value of 283 is reached at 10,000 iterations which occurs in under 15 seconds of computational time.

Another interesting note is that H-CARMA solves this tightly constrained problem in 10,000 iterations and under 15 seconds of computational time. So, not only it finds a high quality solution, but it is also a fast heuristic. By comparison, RH-CARMA takes about 20 minutes.

3. Scenario 3: GOG 90-Day Demonstration with HSV

This scenario is the same as Scenario 2, but with the smaller HSV ship in lieu of the LSD. In comparing these two vessels, the HSV has about 25% of the berthing space the LSD has and about 17% of the LSD's fuel capacity. Compensating this is the fact that the HSV has greatly reduced fuel consumption rates and the minimum fuel capacity is 25% (instead of 60% for the LSD). See Table 1.

a. Results

The results here show how H-CARMA performs with the more restrictive time horizon of 90 days and with less berthing space and fuel capacity. Overall, H-CARMA performs better here when compared to RH-CARMA than in any other scenario presented in this thesis.

Tables 15–16 contain the new schedule for the HSV. Remarkably, this is nearly identical to the LSD's 90-day schedule in Scenario 2. In Table 15, H-CARMA is unable to do all the missions on day 10 with the HSV as it was able to do with the LSD. This is the first time team availability issues are seen in this schedule. Previously, the LSD was able to place a "mesf" team for the port security "MTT" mission. With the smaller berthing space aboard the HSV, H-CARMA schedules this mission with a "usg1" team on day 26 instead. The same number of missions is completed in the same time frame as with previous scenarios, but with different teams.

<table>
<tr><td></td><td>MISSIONS</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td></tr>
<tr><td></td><td>SHIP LOCATION
EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT</td><td>ROTA</td><td colspan="8">UNDERWAY</td><td colspan="25">GHANA*</td></tr>
<tr><td></td><td>UNDERWAY</td><td></td><td colspan="8"></td><td colspan="25"></td></tr>
<tr><td rowspan="18">GHANA*</td><td>MEDICAL OPS/READINESS</td><td colspan="9"></td><td colspan="5">EXMED</td><td colspan="20"></td></tr>
<tr><td>HA/DR OF INFECTIOUS DISEASES</td><td colspan="9"></td><td colspan="3">EXMED</td><td colspan="22"></td></tr>
<tr><td>ENG RECONSTRUCTION SMEE, DIG WELLS</td><td colspan="9"></td><td colspan="10">NCF</td><td colspan="15"></td></tr>
<tr><td>AIRPORT INFRASTRUCTURE IMPROVEMENTS</td><td colspan="9"></td><td colspan="15">NCF</td><td colspan="10"></td></tr>
<tr><td>ROAD IMPROVEMENTS</td><td colspan="9"></td><td colspan="10">NCF</td><td colspan="15"></td></tr>
<tr><td>UTILITY IMPROVEMENTS</td><td colspan="9"></td><td colspan="10">NCF</td><td colspan="15"></td></tr>
<tr><td>INFRASTRUCUTRE GAP ANALYSIS</td><td colspan="24"></td><td colspan="5">NCF</td><td colspan="5"></td></tr>
<tr><td>PUBLIC AFFAIRS SMEE</td><td colspan="9"></td><td colspan="3">MCAG</td><td colspan="22"></td></tr>
<tr><td>BAND LESSONS</td><td colspan="9"></td><td colspan="2">oth.RES</td><td colspan="23"></td></tr>
<tr><td>PORT SECURITY MTT</td><td colspan="24"></td><td colspan="5">USCG1</td><td colspan="5"></td></tr>
<tr><td>SMALL BOAT / BOAT PATROL MAINTENANCE MTT</td><td colspan="9"></td><td colspan="5">SHIP</td><td colspan="20"></td></tr>
<tr><td>ISPS ASSIST / CERT VISIT</td><td colspan="9"></td><td colspan="10">USCG1</td><td colspan="15"></td></tr>
<tr><td>HYDRO SURVEY MTT</td><td colspan="9"></td><td colspan="10">USCG1</td><td colspan="15"></td></tr>
<tr><td>COMMUNICATIONS MTT</td><td colspan="9"></td><td colspan="5">ETC</td><td colspan="20"></td></tr>
<tr><td>OFFICER LEADERSHIP MTT</td><td colspan="9"></td><td colspan="5">SHIP</td><td colspan="20"></td></tr>
<tr><td>NCO PROFESSIONAL DEVELOPMENT SMEE/ MTT</td><td colspan="9"></td><td colspan="3">SHIP</td><td colspan="22"></td></tr>
<tr><td>COOPERATIVE SECURITY LOCATION</td><td colspan="9"></td><td colspan="5">MDA</td><td colspan="20"></td></tr>
<tr><td>AIS RECEIVER SITES CONSTRUCTED</td><td colspan="24"></td><td colspan="10">NCF</td></tr>
</table>

Table 15. H-CARMA Developed Schedule for Days 1-34 in the GOG 90-day Demonstration with HSV.

This table illustrates the routing plan for a HSV ship and the missions to be accomplished in the GOG for days 1-34. With more restrictive berthing, H-CARMA is able to schedule missions with different teams and at different time to maximize total TSC as compared to the GOG 90-day demonstration. The team types conducting the missions are shaded above for the respective mission type and time period for each mission. * denotes countries that provide fuel and supplies.

The “uscg1” team selection seen in Table 15 is made by H-CARMA in the mission packing loop. Since this mission is not able to fit in the schedule with the first group, H-CARMA evaluates it again and schedules it with the second group on day 25. Additionally, it is noted that the team that completes this mission is not the “mesf” team from the LSD scenarios. Here, H-CARMA exhibits its ability to accommodate different teams for missions.

The schedule for the HSV for the remaining days in the interval 35-90 is identical to the LSD schedule of Scenario 2 for the GOG 90-day Demonstration. Thus, despite the HSV has less berthing space, it is able to fit the same teams onboard to complete the same missions on the same days. In this scenario, team availability and the duration of the planning horizon become the more influential factors for H-CARMA.

b. Performance

H-CARMA shrinks the performance gap between itself and RH-CARMA and performs the best here as compared to previous scenarios when comparing these two heuristics. From Table 16, H-CARMA's performance is unchanged from the LSD's 90-day schedule in the previous scenario. However, with the restricted berthing space of the HSV, the RH-CARMA solution worsens to 86% of the LR-CARMA relaxation. This closes the gap between the feasible solutions found by both heuristics to 5%.

Model or Algorithm	TSC	% of LR-CARMA	# of Missions Completed
LR-CARMA	348	100%	66
RH-CARMA	300	86%	56
H-CARMA	283	81%	54

Table 16. H-CARMA Solution Comparative Performance for GOG 90-Day Demonstration with HSV.

This table shows the comparison of H-CARMA's performance to rolling horizon Heuristic RH-CARMA and its linear relaxation LR-CARMA. Results are based on 100,000 iterations in H-CARMA, the HSV Ship, and scenario data provided by CNE-C6F for the 90-day Demonstration with HSV.

When extending this comparison to the issues of scalability and completion time, H-CARMA further establishes it performance value. H-CARMA is still able to solve the problem in 10,000 iterations (as seen in Table 17) in only 15 seconds, as compared to RH-CARMA which requires over 20 minutes.

H-CARMA Performance for HSV 90 Day Routing Schedule			
Iterations	TSC	Cost ($)	# of Missions Completed
1,000,000	283	$8,152,500	54
100,000	283	$8,152,500	54
50,000	283	$8,152,500	54
10,000	283	$8,152,500	54

Table 17. H-CARMA Iteration Performance for GOG 90-Day Demonstration with HSV.

This table shows H-CARMA's performance based on number of iterations run. Best TSC value of 283 is reached at 10,000 iterations which occurs in under 15 seconds of computational time.

Table 18 revisits the inherent issue of limited berthing space on the HSV ship. After a careful review of this table and the routing schedules produced by H-CARMA, it becomes evident that the HSV ship is overloaded. All of the missions scheduled for completion by "etc" teams can be completed by one of these teams instead of the three that are loaded on the HSV. Thus H-CARMA's pre-loading routine and, specifically, the *percentBerthing* parameter of 70% plays a more critical role in determining what missions can be scheduled. In this scenario, 70% may be too large as excess "etc" teams are placed onboard the ship. However, this assessment is based solely on the results obtained by H-CARMA in 100,000 iterations. If mission specifics were not known, it is conceivable that H-CARMA may need these teams to develop a better schedule after many more iterations have allowed more schedules to be developed and tested. H-CARMA demonstrates its ability in continuing to load the ship with necessary teams, but it also underscores the importance and sensitivity the algorithm has to the *percentBerthing* parameter.

Team type	#
ship	3
uscg1	2
nwc	0
eod	0
navelsg	0
ncf	4
comcam	0
riverine	0
mcag	1
etc	3
mesf	0
exmed	2
otherRes	1
mda	1
Total Berthing Used	**99**
	93%

Table 18. HSV Ship Complement: H-CARMA Teams Loaded on HSV for 90-day Routing Schedule in GOG.

This table shows the teams loaded on a HSV ship. Of the 107 berthing spaces available, H-CARMA consumes 99 spaces (93%) to complete 54 of 66 missions possible for a total TSC value of 283 (with 348 being the total possible).

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A. CONCLUSIONS

This thesis has developed a heuristic algorithm, H-CARMA, that produces a feasible solution to the CARMA problem. The solution quality is acceptable for the GOG scenarios used by Spitz for which a comparison with the optimal MIP solution (or with a tight bound) is available. Additionally, H-CARMA effectively copes with the scalability issues present in CARMA for these scenarios, and is not tied to a MIP commercial license, an obstacle for effective deployment of this tool to the Navy.

H-CARMA is a logically constructed heuristic algorithm with selective ordered sets; an enumeration procedure to build feasible schedules; a packing routine to make better use of available resources; and, other assumptions, such as the need to limit the search to in port missions, and the scheme to pre-load the ship with EPTs. Many of these restrict the feasible region where these schedules lie. Despite these restrictions, the results illustrate that H-CARMA performs well and shows promise for future developments.

Specifically, in the scenarios tested, the solution produced by H-CARMA is not only generated in a fraction of the time as compared to RH-CARMA, but the solutions are also only 5% to 7% below the solution it produces. Additionally, by construction, H-CARMA is not affected by scalability. It can handle much larger, conceivable cases, with longer planning horizons and/or country and mission sets, whereas RH-CARMA presents serious issues with scalability.

While optimism is warranted, it is not clear if this accomplishment is attributed to the algorithm, the defined problem, or both. Considering the results of both the LSD and HSV vessels, the problem may have fewer binding constraints than thought. As the HSV is able to complete the same missions as the LSD in a 90-day horizon, the berthing limits and available teams appear to have little impact on the total TSC values collected. Additional testing with different scenarios and adjusting the existing constraints may add

further insight as to the true source of success. Although, finding this source may be of little importance provided the scenarios are accurate for fleet planners; if the results consistently provide high quality solutions, this algorithm becomes a valuable tool. For this realization to occur more scenarios must be developed and tested.

Overall, the basic purpose of H-CARMA in effectively dealing with the scalability inherent in the CARMA problem and in providing fast, quality solutions using license-free software seem to be satisfied by the results presented in this thesis. Based on these findings, future research and development is warranted and encouraged. Suggestions presented below range from minor improvements to the existing algorithm to major developments that include constructing new, independent heuristic algorithms.

B. RECOMMENDATIONS AND FUTURE RESEARCH

One area of improvement is in the acquisition of more scenarios and/or better data. By constructing more scenarios that accurately reflect current fleet planner dilemmas, more can be learned by the developed heuristics and the necessary solution techniques that improve solution quality. From this observation, we present the first two recommendations. These are followed by other potential improvements pertaining to the H-CARMA heuristic.

1. Data Refinement

a. Refueling and Resupply

H-CARMA assumes that the ship replenishes its fuel and supplies every day it is located at a port that is capable of providing. Furthermore, this algorithm assumes that the quality of fuel and supplies is both homogenous and at no cost. While this simplifies modeling and the construction of algorithms, it does not accurately reflect the reality decision makers face. An associated cost with the refueling and provisioning activities will likely influence the outcome of the results obtained.

b. Teams and Team Availability

Given the results, the number of teams, or the missions that required these teams, are not as restrictive as thought. Decision makers may decide that some teams are more available from the homeport than others. Current data used is generous with the number and type of teams available, so H-CARMA is not challenged as much as it could be. By incorporating realistic restrictions on team availability, or even their cost, more insight may be gained.

2. Specific Algorithm Improvements

a. Budget Reductions

In the MIP-CARMA model, reducing costs is a secondary goal after the total TSC is maximized. H-CARMA currently does not minimize cost. Adding this capability to H-CARMA not only makes it more comparable to the output generated by RH-CARMA, but this also addresses the inherent concerns any decision maker would have in reducing operational costs.

b. Mission Ordering

H-CARMA is very sensitive to the ordering of its (mission, country) pairs. As seen in the results earlier, the first half of every schedule looks nearly identical. While this is naturally due to the enumeration process, possible improvements may be realized by changing how this selective ordering is accomplished. For example, if the (mission, country) pairs were ordered by proximity from homeport instead of TSC, the outcome in the schedules will be very different.

c. In Port Missions

H-CARMA assumes that all missions require the ship to stay in port. If H-CARMA allowed the ship to drop teams off to conduct those missions that do not require the ship to stay in port, better schedules may be obtained. By forcing the ship to stay in port for all missions directly implies that: (a) the ship will incur higher total costs

due to the port costs incurred; and (b) idle time spent by the ship in port (waiting for missions to finish) could have been used to accomplish missions in other countries, especially when the length of the planning horizon is a binding constraint.

d. Team Selection and Handling

From the H-CARMA results, it is noted that initially loading the ship with teams may result in a number of outcomes that are not explicitly dealt with by the current heuristic. In the results presented, several teams that were loaded on the ship were not used. While this does not appear to be a problem for the scenarios presented, future scenarios may prove more challenging. A number of hypothetical possibilities exist where pre-loading the ship by 70% with teams could adversely affect H-CARMA's performance. Additionally, there are similar cases where not pre-loading the ship could also adversely affect the heuristics performance. Thus, it stands to reason that pre-loading the ship to some level is beneficial for most scenarios. It is left to future research to determine how much pre-loading should or should not be done in H-CARMA for future scenarios.

Similarly, the preloading assumption that "as many teams of the most-valuable type should be added first, and so forth," may not be adequate. For example, only one team of a preferred type may suffice if all the missions the team must accomplish occur in different time periods. While that cannot be fully anticipated a priori, some preprocessing of the data may help determine not just the team order by type, but also a more balanced number of teams of each type. Alternatively, when no more teams can be added to the ship, H-CARMA could implement some strategy to eliminate unused teams during execution in order to make room for other teams to be added.

e. System of Subsets

Another potential enhancement consists of creating subsets of the (mission, country) pairs and have H-CARMA enumerate through one or each of these smaller subsets. Depending on the number of permutations involved, H-CARMA may be

able to exhaust all possibilities in each subset. After these solutions are found in the subsets, the algorithm can be constructed to combine these subsets together while there is still time available in the problem's specified time horizon. While ensuring that feasibility is maintained across these combined subsets, H-CARMA may gain an advantage in exhausting all permutations available in these smaller subsets. Given various restrictions, H-CARMA will be able to find the optimal value for the subset(s) and combine them for an overall solution.

3. Alternative Implementations

A better implementation may be achieved by eliminating the use of the recursive call to enumerate the (mission, country) pairs, currently used by H-CARMA, which incurs in a high computational burden as full copies of stack elements are continuously made. This may enable to test more feasible schedules in the same amount of time.

The new algorithm would rely on explicitly updating a set of data structures and variables to capture the state of the problem each time it chooses a (mission, country) pair. Only by explicitly recording the state of the problem (i.e. the current schedule, the ship parameters, the teams, etc.) can the algorithm return to an earlier decision point when it backtracks.

In this algorithm, no mission packing would take place and the in port assumption is discarded. Additionally, (mission, country) pairs would not have to be selectively ordered, although it is expected that some ordering will be advantageous.

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